*Article*

# Industry 4.0 (I4.0) Based Virtual Organization Model for the Coordination of Sustainable Textile Supply Chain

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## ABSTRACT

The lack of attention on the forward and backward supply chain issues, i.e., the transparency between supply chain agents, information sharing, resource deployment, workforce knowledge, waste reduction, cost efficiency, and resource management are the major problems of textile supply chain. The coordination of forward and backward supply chain becomes difficult due to the players' self-interest and firmographics. It becomes much complicated when we consider the triple bottom line of sustainability (TBLS) in the supply chain. Therefore, in this paper, we propose an Industry 4.0 (I4.0) based virtual organization model for the coordination of the forward and backward supply chain. The results obtained through virtual organization model are also compared with the centralized supply chain and traditional cost-sharing contract. The results reveal that virtual organization model can perform better than the price only contract and it will be help firms in achieving greater sustainability with respect to traditional contract mechanisms.

## KEYWORDS

Industry 4.0 (I4.0), Virtual Organization, Sustainable Innovation, Supply Chain, Channel Coordination

## INTRODUCTION

The speech of sixteen-year-old Swedish girl Greta Thunberg on climate change and sustainability at the United Nations Climate Action Summit in New York in 2019 has garnered significant attention from business leaders and policy-makers across the globe[1]. According to the chief executives of many of the world's largest organizations, businesses are failing to meet sustainability challenges[2]. A survey by United Nation Global Compact and Accenture reveals that only 21% of businesses are contributing to global sustainability, whereas fewer than half are integrating sustainability into their businesses. In another survey, it was revealed that around ten thousand companies have shut down due to environmental issues[3]. The oil and textile industry are top two polluting industry in the world[4].

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[1] Trapp, R. (2019, September 24). CEOs Call for More Urgency on Sustainability. Retrieved October 29, 2019, from https://www.forbes.com/sites/rogertrapp/2019/09/24/ceos-call-for-more-urgency-on-sustainability/#4085a1657442
[2] Ibid 1
[3] Ibid 1
[4] Pandey, K. (2018, July 19). Fashion industry may use quarter of world's carbon budget by 2050. Retrieved October 29, 2019, from https://www.downtoearth.org.in/news/environment/fashion-industry-may-usequarter-of-world-s-carbon-budget-by-2050-61183

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According to McKinsey, 1 Kg of denim fabric (from fiber to fabric stage) produces 23 kg greenhouse gases on average[5]. Furthermore, it was found that the textile industry releases1.2 billion tons greenhouse gas annually, which is higher than the combined emission from the international flights and the shipping industry across the globe[6]. Additionally, research in the domain of sustainability indicates several studies that examine forward as well as backward supply chain issues (de Castro Vivas, Sant'Anna, Esquerre, & Freires, 2019; Fallahpour, Olugu, Musa, Wong, & Noori, 2017; Ghadimi, Wang, Lim, & Heavey, 2019). Many researchers have incorporated the green, social, and sustainability attributes in supply chain coordination (Cai, Chen, Siqin, Choi, & Chung, 2019; Guo, Qu, Tseng, Wu, & Wang, 2018; Halat & Hafezalkotob, 2019; Hong & Guo, 2019; Madani & Rasti-Barzoki, 2017; Ni & Li, 2012; Ni, Li, & Tang, 2010; Seyedhosseini, Hosseini-Motlagh, Johari, & Jazinaninejad, 2019; Song & Gao, 2018). However, no study to date has examined the sustainable supply chain coordination in the context of industry 4.0 (I4.0). I4.0 integrates the internet of things (IoT) and the information management system to manage complex business issues (Dolgui, Ivanov, Sethi, & Sokolov, 2019; Ghadimi et al., 2019; Luthra, Kumar, Zavadskas, Mangla, & Garza-Reyes, 2019; Manavalan & Jayakrishna, 2019; Rajput & Singh, 2019; Rauch, Linder, & Dallasega, 2019; Vernadat, Chan, Molina, Nof, & Panetto, 2018).

Therefore, in this study, we examine I4.0 based virtual organization (Ahonen, de Alvarenga, & Provedel, 2009; Camarinha-Matos, Afsarmanesh, Galeano, & Molina, 2009; Huang, Hu, & Li, 2004; Park & Favrel, 1999; W. Y. Wang & Chan, 2010; Xu, Wei, & Fan, 2002) as a central planer for the improved performance of the entire supply chain. Specifically, we take into account I4.0 based virtual organization as a central planer for the enhanced performance of the whole supply chain. While exploring the applicability of I4.0 based virtual organization for the sustainable supply chain coordination, our objective will be to uncover the following research questions:

(i) How does the I4.0 based virtual organization model will help in achieving coordination between forward and backward supply chains?
(ii) How is the Virtual organization model better than the traditional coordination mechanisms?
(iii) What will be the impact of sustainability parameters on the performance measures of the supply chain?
(iv) How is the consumer sensitivity to sustainable performance related to the performance measures of supply chain agents?

The proposed model is examined with reference to textile industry. Textile industry is the second most polluting industry across the globe[7] and therefore presents the exemplary scenario for exploring the relationships posited in this study. The textile supply chain consists of a large number of channel partners such as fiber producer, yarn manufacturer, greige fabric manufacturer, textile processor, dyer, finishing unit, garment manufacturer, and so forth. Due to the involvement of many players with different self-interest and firmographics, it becomes challenging to coordinate the entire supply chain. The supply chain coordination becomes much complicated when we focus on sustainability factors for the agents. Sustainability in the supply chain refers to the adoption of environmental, social, and economic practices by the supply chain members (de Sousa Jabbour, Jabbour, Foropon, & Godinho Filho, 2018). These three pillars (environmental, social, and economic performance) are known as the triple bottom line of sustainability (Elkington, 1998). The triple bottom line of sustainability is becoming essential for practitioners because of environmental norms, government regulations, customer social pressure, and pressure of external stakeholders (Mani & Gunasekaran, 2018; Sandrin,

[5] The environmental costs of creating clothes. (2017, April 11). Retrieved October 29, 2019, from https://www.economist.com/the-economist-explains/2017/04/11/the-environmental-costs-of-creating-clothes
[6] Ibid 4
[7] Ibid 4

Trentin, & Forza, 2018.)

In response to it, many leading apparel and fashion brands have been urged to incorporate sustainable practices in the supply chain. For example, many companies like Beaumont Organic, Bottletop, Braintree Clothing, The Ethical Silk Co, Gilda & Pearl, Kuyichi, Lur Apparel, MIMCO, and Nudie Jeans are taking a stand to eliminate issues of unsustainable practices via various environmental and social practices[8].

Information technology is the enabler of virtual organization, i.e., virtualization of teams, communities, enterprises, supply chains, and organizations (Chamakiotis, Boukis, Panteli, & Papadopoulos, 2020; Chou & Hsu, 2018; Hsieh, Lin, & Chiu, 2002; Kim, Song, & Jones, 2011; Olaisen & Revang, 2017). Virtual organization refers to the collection of geographically distributed, functionally, and culturally diverse entities that are linked by electronic forms of communication and rely on lateral, dynamic relationships for coordination (Desanctis & Monge, 1999). In other words, Industry 4.0 (I4.0) based virtual organization is a form of temporary association in which two or more firms coordinate with each other to achieve specific goals (Davidow & Malone, 1992).

I4.0 based virtual organization has capabilities to solve the problems of forward and backward supply chain simultaneously (Molina, Velandia, & Galeano, 2007; W. Y. C. Wang & Chan, 2010). It can help in reducing cost and lead time simultaneously (Shafiq, Sanin, Szczerbicki, & Toro, 2016; Shafiq, Sanin, Toro, & Szczerbicki, 2015). It has the potential to transform the relationship between supply chain agents by diminishing the power disparity (Lu, 2017). It can enable sustainable performance in the supply chain (Luthra et al., 2019). It can help in the flexible allocation of resources (Hughes, O'Brien, Randall, Rouncefield, & Tolmie, 2001). It can help in gaining virtual control over the supply chain agents (Ben-Daya, Hassini, & Bahroun, 2019). It can improve the effectiveness of virtual entities (Ahuja & Carley, 1999).

W. Y. Wang and Chan, 2010 also highlighted the importance of virtual organization and suggested the role of a single authority for the easier management of supply chains. A virtual organization is important for the integration and strategic alliance between firms (McCarter & Northcraft, 2007; Talluri, Baker, & Sarkis, 1999). In real-life cases, there are several examples of virtual organizations, i.e., the alliance between Apple and Sony for the development of Powerbook[9]; alliance among IBM, Apple, and Motorola for the development of the microprocessor and operating system[10]; Hewlett-Packard and Disney[11], etc.

The proposed virtual organization model for the coordination of forward and backward supply chain is also compared with the centralized supply chain and cost-sharing contract. The non-cooperative game-theoretical approach has been used for the analysis of models. The analytical and numerical simulation-based results of this study reveal that I4.0 based virtual organization model can perform better than the price-only contract (wholesale price contract). Furthermore, the virtual organization model can be helpful for firms in achieving a higher level of sustainability than some of the existing traditional supply chain contracts.

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[8] 15 Ethical and Sustainable Fashion Companies You Should Know About. (2015, May 22). Retrieved October 29, 2019, from https://www.business2community.com/fashion-beauty/15-ethical-and-sustainable-fashion-companies-you-should-know-about-01232405

[9] Chief Executive. (1992, November 1). Strategic Alliances: Overcoming Barriers to Success. Retrieved October 29, 2019, from https://chiefexecutive.net/strategic-alliances-overcoming-barriers-to-success__trashed/

[10] Markoff, J. (1997, September 9). Motorola and I.B.M. Look Beyond Chip Pact with Apple. Retrieved October 29, 2019, from https://www.nytimes.com/1997/09/09/business/motorola-and-ibm-look-beyond-chip-pact-with-apple.html

[11] Kamau, N. (2019, May 24). Successful Strategic Alliances: 5 Examples of Companies Doing It Right. Retrieved October 29, 2019, from https://www.allbound.com/blog/successful-strategic-alliances-5-examples-of-companies-doing-it-right

The remainder of the paper is organized as follows. Section 2 presents the methodology, including virtual organization model, assumptions, centralized decision making, and traditional contract mechanisms were discussed. Section 3 shows the analytical results of the models. In section 4, numerical simulation and graphical analysis, along with the significant findings, are discussed. Section 5and 6 show the discussion and conclusion (limitation and future research perspectives), respectively.

## METHODOLOGY

In this section proposed model, assumptions of the model, centralized supply chain, and cost-sharing contact are presented.

### *MODEL*

The model proposed in this paper is grounded on the virtual organization model discussed by (W. Y. Wang and Chan (2010)). It is assumed that the manufacturer and retailer are coordinating with each other via the formation of I4.0 based virtual organization (see Figure 1). The manufacturer is responsible for fiber procurement, yarn manufacturing, greige fabric manufacturing, pretreatment, dyeing, finishing, garment manufacturing, product planning and control, and sourcing of raw materials (Example: Vardhman Textile Limited, Arvind Mills, and other integrated textile manufacturing firms). On the other hand, the retailer is responsible for promotion, advertisement, sales, demand forecasting, and sustainable innovation (Example: Patagonia, Zara, H&M, and other leading fashion retailers). After the formation of a centralized virtual organization platform, both parties share information with each other regarding design, order size, lead time, product specification, fiber type, yarn specifications, weave types, chemical processing parameters, and so forth (see Figure 1). The relationship between manufacturer and retailer is studied with the help of game-theoretic analysis. The results obtained through the proposed model are also compared with the cost-sharing contract. The notations used in this paper are shown in the following Table 1.

**Table 1.** Notations Used in the Model

| S. No. | Parameters and Decision Variables | Notations |
|---|---|---|
| 1 | *Market potential* | $a$ |
| 2 | *Consumer sensitivity to price* | $b$ |
| 3 | *Per unit variable cost of manufacturer* | $c$ |
| 4 | *Consumer sensitivity to sustainable innovation* | $\alpha$ |
| 5 | *Sustainable innovation level* | $\theta$ |
| 6 | *Cost parameter of sustainable innovation* | $I$ |
| 7 | *Investment of manufacturer in I4.0* | $v_1$ |
| 8 | *Investment of retailer in I4.0* | $v_2$ |
| 9 | *Demand expansion coefficient due to I4.0 based virtual organization* | $\beta$ |
| 10 | *Cost reduction coefficient due to I4.0 based virtual organization* | $\gamma$ |
| 11 | *Manufacturer's profit* | $\pi^M$ |
| 12 | *Retailer's profit* | $\pi^R$ |
| 13 | *Centralized supply chain profit* | $\pi_*^{SC}$ |
| 14 | *Margin of retailer* | $m$ |
| 15 | *Wholesale price of manufacturer* | $w$ |
| 16 | *Retail price* | $p$ |
| 25 | *Cost-sharing coefficient of manufacturer* | $\psi$ |
| | **Contract and Decision Making** | |
| 19 | *Cost-sharing contract* | *CSC* |
| 22 | *Centralized decision making* | * |
| 23 | *Virtual organization model* | *VO* |

***ASSUMPTIONS OF THE MODEL***

a) The manufacturer and the retailer are individually rational and risk-neutral in nature.
b) The manufacturer produces only one product, and the retailer is considered to sell only one product.
c) Consumers are sensitive towards sustainable innovation performed by supply chain agents. Examples of sustainable innovation in the textile supply chain are fluorine and formaldehyde-free finishing, biopolishing, bio-scouring, bio-desizing, natural dyes, waterless dyeing, and so forth.
d) The sustainable innovation is done by the retailer, which is Stackelberg leader and the manufacturer is Stackelberg follower. Example: In the fashion industry, H&M, Nike, M&S, ZARA, etc., are leaders who are well known for sustainable practices. Small manufacturers from Asian countries are assumed to be Stackelberg follower.
e) The demand for the product is assumed to be linear and deterministic in nature.
f) The demand function is dependent on price, and sustainable innovation level, as shown follows:

$$q = a - p + \alpha\theta$$

g) Retail price is assumed to be the sum of the wholesale price and retail margin as given as follows:

$$p = w + m$$

h) Both the manufacturer and retailer are investing in the information system. As a response to it, the upstream firm, i.e., the manufacturer will get the benefit of reduced operational cost, and the retailer will get the benefit of increased sales (refer to Figure 1). The operational cost will reduce due to the increased efficiency, waste reduction, and transparent information (Shafiq et al., 2015, 2016; W. Y. Wang & Chan, 2010). The sales will increase due to better forecasting, transparent market information, advertisement, etc. (W. Y. C. Wang & Chan, 2010; W. Y. Wang, Pauleen, & Chan, 2013).

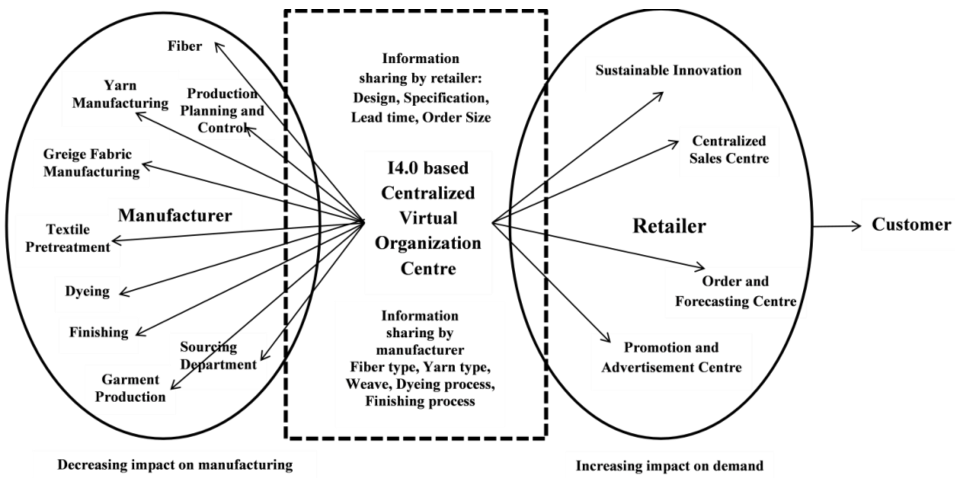


**Figure 1.** Channel Coordination through Virtual Organization

The profit function of manufacturer and retailer in the proposed virtual organization model is shown as follows:

$$\pi_{VO}^{M} = \{w - c(1-\gamma)\}q(1+\beta) - v_1$$

$$\pi_{VO}^{R} = mq(1+\beta) - I\theta^2 - v_2$$

In the proposed model, first of all, on the basis of the manufacturer's response function, the retailer decides his profit margin, level of sustainable performance, and level of investment. Then in the second stage, the manufacturer decides her wholesale price and the investment level. The backward induction method has been used for the derivation of equilibrium results. The equilibrium level of sustainable innovation, retail price, demand, wholesale price, profit margin, channel efficiency, individual agent's and total supply chain profit are shown in table 4. The performance measures of the proposed virtual organization model are also compared with the performance of the centralized supply chain and cost-sharing contract, which are shown as follows.

### CENTRALIZED SUPPLY CHAIN

In the centralized supply chain, it is considered that only one decision-maker takes the decision on the level of retail price and level of sustainable performance. The profit function of the centralized supply chain is given below.

$$\pi_*^{SC} = (p - c)q - I\theta^2$$

### COST-SHARING CONTRACT

The cost-sharing contract is frequently used in real-life business practices in which manufacturer and retailer shares cost for new product development. In a cost-sharing contract, first of all, the manufacturer decides her cost-sharing fraction given the response function of the retailer. After that, the retailer decides his profit margin and level of sustainability considering the manufacturer's response function. At the end of the game, the manufacturer decides her wholesale price given the level of cost-sharing fraction, profit margin, and level of sustainability. The backward induction method is used to derive the equilibrium results (shown in Table 2). The profit function of manufacturer and retailer will be as follows.

$$\pi_{CSC}^{M} = (w - c)q - \psi I\theta^2$$

$$\pi_{CSC}^{R} = mq - (1 - \psi)I\theta^2$$

**Table 2.** Decision Making and Game Construct

| S. No. | Decision Making | Contract | Game | Game Construct |
|---|---|---|---|---|
| 1 | *Coordinated* | *Virtual organization model* | *RS* | *R decides $m, \theta, v_2$ → M decides $w, v_1$* |
| 2 | *Centralized* | - | - | *Centralized supply chain decide $p_1, \theta_1$* |
| 3 | *Coordinated* | *CSC* | *RS* | *M decides $\psi$ → R decides $m, \theta$ → M decides w* |

## ANALYTICAL RESULTS

In this section, the analytical results of the proposed model, centralized supply chain, and the cost-sharing contract are discussed (as shown in Table 3).

***Proposition 1:*** *If $\{6I - (1 + \beta)\alpha^2\} > 0$, then $\frac{\partial w_{VO}}{\partial \gamma} < 0$ and $\frac{\partial m_{VO}}{\partial \gamma} > 0$.*

This proposition is derived from the differentiation of optimal wholesale price and profit margin of VO model with respect to cost reduction coefficient. After differentiating $w_{VO}$ with respect to $\gamma$, we get, $\frac{\partial w_{VO}}{\partial \gamma} = \frac{-c\{6I-(1+\beta)\alpha^2\}}{\{8I-(1+\beta)\alpha^2\}}$. Therefore, $\frac{\partial w_{VO}}{\partial \gamma} < 0$if $\{6I - (1 + \beta)\alpha^2\} > 0$. Similarly, after differentiating $m_{VO}$ with respect to $\gamma$, we get, $\frac{\partial m_{VO}}{\partial \gamma} = \frac{c}{\{8I-(1+\beta)\alpha^2\}} > 0$. This shows that, as the reduction coefficient increases, the wholesale price decreases, and the profit margin increases. Therefore, investment

in the virtual organization by manufacturer and retailer results in positive outcomes in terms of the decreased wholesale price and increased profit margin. The operational cost of the manufacturer has several components such as sourcing cost of cotton, spinning cost, weaving cost, chemical processing cost, dyeing cost, finishing cost, garmenting cost, and so forth. Similarly, the operational cost of the fashion retailer has different components such as procurement cost, inventory cost, rent, salary, sustainable innovation cost, promotion and advertisement cost, and so forth. The proposed virtual organization for the textile industry can be helpful in reducing the operational cost of both channel partners (manufacturer and retailer). Hence, it lowers the wholesale price of the integrated manufacturer and increases the profit margin of the retailer.

> ***Proposition 2:*** *In the virtual organization model, the wholesale price of the manufacturer increases with the increase in demand expansion coefficient ($\beta$).*

This proposition is derived from the differentiation of optimal wholesale price ($w_{VO}$) of the manufacturer with respect to demand expansion coefficient ($\beta$). After differentiating $w_{VO}$ with respect to $\beta$, we get, $\frac{\partial w_{VO}}{\partial \beta} = \frac{2I\alpha^2(a-c+c\gamma)}{\{8I-(1+\beta)\alpha^2\}^2} > 0$. This shows that, as the coefficient of demand expansion ($\beta$) increases, the wholesale price ($w_{VO}$) increases. It may be due to the higher cost of sustainable innovation of the manufacturer, which is essential to be performed to fulfill the demand of sustainability-conscious customers. In the proposed model, it is assumed that the demand for the product is dependent on the level of sustainability. One of the important characteristics of the proposed VO model is the ability to increase the demand for the fashion products. The increase in the demand for the fashion products can be due to important features of VO models such as reduction in the cycle time, proper information sharing across the supply chain, developing the new market, fulfilling the dynamic demand, and so forth. As the level of demand for sustainable product increases, the level of investment for sustainable innovation increases in quadratic form (i.e.,$I\theta^2$). Therefore, the operational cost of the retailer increases, which can have an increasing impact on the wholesale price of the integrated manufacturer.

> ***Proposition 3:*** *In the virtual organization model, the profit margin of the retailer decreases with the increase in demand expansion coefficient ($\beta$).*

The proposition is derived from the optimal profit margin of the retailer given in Table 4. After differentiating $m_{VO}$ with respect to $\beta$, we get, $\frac{\partial m_{VO}}{\partial \beta} = \frac{-4I\alpha^2(a-c+c\gamma)}{\{8I-(1+\beta)\alpha^2\}^2} < 0$. This relationship indicates that the profit margin of the retailer in the virtual organization model decreases with the increase in demand expansion coefficient. It can be due to the higher cost of manufacturing and increased level of wholesale price by the manufacturer. In the Proposition 2, it is found that the demand expansion coefficient ($\beta$) has an increasing impact on the wholesale price of the integrated manufacturer. In the textile supply chain, fashion retailer procures the finished fashion products from the manufacturer and pays wholesale price to the manufacturer for the finished fashion product. As the level of wholesale price increases due increase in the demand coefficient ($\beta$), the overall cost of the retailing increases. Therefore, the profit margin of the retailer can decrease due to the demand expansion coefficient ($\beta$). Additionally, the fashion retailer is responsible for sustainable innovation. The demand for the product increases with respect to the demand expansion coefficient, which leads to the more investment in sustainability. Therefore, the sustainable innovation investment increases with respect to demand expansion coefficient, and hence the total cost of retailer increases, which has a decreasing impact on the profit margin of retailer.

***Proposition 4:** In the virtual organization model, cost reduction coefficient $(\gamma)$ and demand expansion coefficient $(\beta)$ has an increasing impact on the demand for the product $(q_{VO})$.*

This proposition is derived from the differentiation of product demand $(q_{VO})$ in virtual organization model with respect to cost reduction coefficient $(\gamma)$ and demand expansion coefficient $(\beta)$ followed by algebraic simplifications. After differentiating $q_{VO}$ with respect to $\gamma$, we get, $\frac{\partial q_{VO}}{\partial \gamma} = \frac{2I(1+\beta)c}{\{8I-(1+\beta)\alpha^2\}} > 0$. Furthermore, after differentiating $q_{VO}$ with respect to $\beta$, we get, $\frac{\partial q_{VO}}{\partial \beta} = \frac{[2I(a-c+c\gamma)\{8I-(1+\beta)\alpha^2\}+2I(1+\beta)(a-c+c\gamma)\alpha^2]}{\{8I-(1+\beta)\alpha^2\}^2} > 0$. This proposition reveals that, as the cost reduction coefficient $(\gamma)$ increases, $q_{VO}$ increases. Additionally, as the level of demand expansion coefficient $(\beta)$ increases, the product demand in the VO model increases. The proposed Industry 4.0 based VO model consists of important technologies such as the internet of things (IoT), cloud computing, RFID, artificial intelligence, robotics, machine learning, big data, cybersecurity, system integration, and so forth. These technologies enable the textile supply chain to share the demand information, process the demand information, and getting important insights about the dynamic demand. Furthermore, the proposed VO model helps the textile supply chain to respond to the customer's demand in a faster way as compared to the traditional textile supply chain. Therefore, the Industry 4.0 based VO model can help the textile supply chain to generate higher demand as compared to the traditional supply chain.

***Proposition 5:** In the virtual organization model, cost reduction coefficient $(\gamma)$ and demand expansion coefficient $(\beta)$ has an increasing impact on the sustainability level $(\theta_{VO})$.*

The proposition is derived from the differentiation of optimal sustainability $(\theta_{VO})$ in the virtual organization model with respect to cost reduction coefficient $(\gamma)$ and demand expansion coefficient $(\beta)$. After differentiating $\theta_{VO}$ with respect to $\gamma$, we get, $\frac{\partial \theta_{VO}}{\partial \gamma} = \frac{\alpha(1+\beta)c}{\{8I-(1+\beta)\alpha^2\}} > 0$. Furthermore, after differentiating $\theta_{VO}$ with respect to $\beta$, we get, $\frac{\partial \theta_{VO}}{\partial \beta} = \frac{[\alpha(a-c+c\gamma)\{8I-(1+\beta)\alpha^2\}+\alpha(1+\beta)(a-c+c\gamma)\alpha^2]}{\{8I-(1+\beta)\alpha^2\}^2} > 0$. This proposition reveals that the virtual organization model leads to a higher level of sustainability. The cost reduction coefficient $(\gamma)$ and demand expansion coefficient $(\beta)$, both have an increasing impact on the level of sustainability. The proposed VO model has the ability to reduce the cost as well as increase the demand for the fashion product. The reduction in the cost can be due to lower labor cost, process improvement, better coordination, and reduction in the inventory cost, while the increase in the demand can be due to uniform information sharing, better information processing, and reduction in the cycle time to fast fashion products. These both factors can improve the sustainability level of the entire supply chain simultaneously. Therefore, in order to achieve a higher level of sustainability, supply chain agents should form the virtual organization model to coordinate with supply chain partners.

***Proposition 6:** In the virtual organization model, cost reduction coefficient $(\gamma)$ has (a) decreasing impact on the price $(p_{VO})$ if $\{2I-(1+\beta)\alpha^2\} > 0$ and (b) increasing impact on the price $(p_{VO})$ if $\{2I-(1+\beta)\alpha^2\} < 0$.*

This proposition is derived from the differentiation of optimal price ($p_{VO}$) in the virtual organization model with respect to cost reduction coefficient ($\gamma$). After differentiating $p_{VO}$with respect to $\gamma$, we get, $\frac{\partial p_{VO}}{\partial \gamma} = \frac{-\{2I-(1+\beta)\alpha^2\}c}{\{8I-(1+\beta)\alpha^2\}}$. If $\{2I - (1+\beta)\alpha^2\} > 0$ then, $\frac{\partial p_{VO}}{\partial \gamma} < 0$, and if $\{2I - (1+\beta)\alpha^2\} < 0$ then, $\frac{\partial p_{VO}}{\partial \gamma} > 0$. This proposition shows that in a specific condition, the cost reduction coefficient ($\gamma$) has an increasing and decreasing impact on the optimal level of price ($p_{VO}$). In the case (a), the simplification of $\{2I - (1+\beta)\alpha^2\} > 0$ results in $\left\{\frac{2}{(1+\beta)}\right\} > \frac{\alpha^2}{I}$. The term $\left(\frac{\alpha^2}{I}\right)$represents the total sustainability effort of the proposed VO model. Therefore, if the total sustainability effort of the VO model is lesser than$\left\{\frac{2}{(1+\beta)}\right\}$, the price of sustainable fashion product will reduce with respect to the cost reduction coefficient ($\gamma$). However, if the total sustainability effort of the VO model is more than $\left\{\frac{2}{(1+\beta)}\right\}$, the price of sustainable fashion product will increase with respect to the cost reduction coefficient ($\gamma$). Therefore, $\left\{\frac{2}{(1+\beta)}\right\}$ is the critical level of sustainability effort of the proposed VO model (at which the non-linear trend of the relative change of price with respect to cost reduction coefficient). Furthermore, the critical level of total sustainability is inversely proportional to the level of demand expansion coefficient ($\beta$).

***Proposition 7:*** *In the virtual organization model, the demand expansion coefficient ($\beta$) has an increasing impact on retail price ($p$).*

This proposition is derived from the differentiation of optimal price ($p_{VO}$) in the virtual organization with respect to the demand expansion coefficient ($\beta$), After differentiation and algebraic simplifications, we get, $\frac{\partial p_{VO}}{\partial \beta} = \frac{6I\alpha^2(a-c+c\gamma)}{\{8I-(1+\beta)\alpha^2\}^2} > 0$. This proposition reveals that the optimal level of the retail price ($p_{VO}$) increases with the increase in the demand expansion coefficient ($\beta$). This may be due to the fact that the increased product demand leads to more investment in sustainability and therefore increase the overall price of the product. In the proposed VO model, the fashion retailer is assumed to perform sustainable innovation. The examples of sustainable innovation in the textile industry are organic cotton, natural fibers, natural dyes, enzymatic treatments, eco-friendly chemicals, waterless dyeing, energy-efficient technologies, and so forth. The cost of the sustainable innovation follows the quadratic relationship with the level of innovation. The level of sustainable innovation increases with respect to the demand expansion coefficient ($\beta$), which increases the total cost of the retailer, consequently the retail price of sustainable product increases.

***Proposition 8:*** *The investment in the virtual organization by the manufacturer ($v_1$) and by the retailer ($v_2$) follows the following properties:*

*(a) If the cutoff profit level of the manufacturer is $\bar{\pi}^M_{min}$, then $v_1 \leq \left[\frac{4I^2(a-c+c\gamma)^2(1+\beta)}{(\beta\alpha^2 - 8I + \alpha^2)^2} - \bar{\pi}^M_{min}\right]$*

*(b) If the cutoff profit level of the retailer is $\bar{\pi}^R_{min}$, then $v_2 \leq \left[\frac{I(\beta+1)(a-c+c\gamma)^2}{[(-\beta-1)\alpha^2 + 8I]} - \bar{\pi}^R_{min}\right]$*

*(c) $\frac{\partial v_1}{\partial \beta} > 0$ and $\frac{\partial v_1}{\partial \gamma} > 0$*

*(d) $\frac{\partial v_2}{\partial \beta} > 0$ and $\frac{\partial v_2}{\partial \gamma} > 0$*

This proposition is derived from the manufacturer and retailer's profit in the virtual organization model (see Table 3). If the cutoff profit level of the manufacturer is $\bar{\pi}_{min}^{M}$, then the manufacturer will be ready to form the virtual organization model if $\frac{4I^2(a-c+c\gamma)^2(1+\beta)}{(\beta\alpha^2-8I+\alpha^2)^2} - v_1 \geq \bar{\pi}_{min}^{M}$, thus $v_1 \leq \left[\frac{4I^2(a-c+c\gamma)^2(1+\beta)}{(\beta\alpha^2-8I+\alpha^2)^2} - \bar{\pi}_{min}^{M}\right]$. Similarly, if the cutoff profit level of the retailer is $\bar{\pi}_{min}^{R}$, then, the retailer will be ready to form the virtual organization model if $\frac{I(\beta+1)(a-c+c\gamma)^2}{[(-\beta-1)\alpha^2+8I]} - v_2 \geq \bar{\pi}_{min}^{R}$, thus $v_2 \leq \left[\frac{I(\beta+1)(a-c+c\gamma)^2}{[(-\beta-1)\alpha^2+8I]} - \bar{\pi}_{min}^{R}\right]$. If $v_1 = \left[\frac{4I^2(a-c+c\gamma)^2(1+\beta)}{(\beta\alpha^2-8I+\alpha^2)^2} - \bar{\pi}_{min}^{M}\right]$, then taking the partial derivative of $v_1$ w.r.t. $\beta$ and $\gamma$, we get, $\frac{\partial v_1}{\partial \beta} = \frac{4I^2(a-c+c\gamma)^2[(-\beta-1)\alpha^2+8I][(\beta+1)\alpha^2+8I]}{[(-\beta-1)\alpha^2+8I]^4} > 0$, and $\frac{\partial v_1}{\partial \gamma} = \frac{8I^2c(a-c+c\gamma)(1+\beta)}{[(-\beta-1)\alpha^2+8I]^2} > 0$. If $v_2 = \left[\frac{I(\beta+1)(a-c+c\gamma)^2}{[(-\beta-1)\alpha^2+8I]} - \bar{\pi}_{min}^{R}\right]$, then taking the partial derivative of $v_2$ w.r.t. $\beta$ and $\gamma$, we get, $\frac{\partial v_2}{\partial \beta} = \frac{8I^2(a-c+c\gamma)^2}{[(-\beta-1)\alpha^2+8I]^2} > 0$ and $\frac{\partial v_2}{\partial \gamma} = \frac{2Ic(a-c+c\gamma)(1+\beta)}{[(-\beta-1)\alpha^2+8I]} > 0$. In the proposed VO model, integrated manufacturer and fashion retailer are responsible for investment in Industry 4.0 technologies such as the internet of things (IoT), robotics, system integration, and so forth. Additionally, both the channel partners invest in the establishment of the core infrastructure of the virtual organization such as procurement planning center, unified sales center, headquarter of virtual organization, and so forth. This proposition provides important insights into supply chain agents for the investment in virtual organization model and can help them to decide the level of investment. It is also found that as the demand and cost reduction coefficient increases, the level of investment increases. Therefore, in order to get better performance of the VO model, higher investment is required in the information system.

**Table 3.** Equilibrium Results of Models

| S. No. | Optimal Decisions | Centralized | CSC | I4.0 Based Virtual Organization |
|---|---|---|---|---|
| 1 | $w$ | - | $\left[\frac{\left(16aI+48cI-a\alpha^2-11c\alpha^2\right)}{4(-3\alpha^2+16I)}\right]$ | $\left[\frac{2I(a-c+c\gamma)}{(-\beta-1)\alpha^2+8I}-c(\gamma-1)\right]$ |
| 2 | $m$ | - | $\left[\frac{\left\{(-\alpha^2+16I)(a-c)\right\}}{-6\alpha^2+32I}\right]$ | $\left[\frac{4I(a-c+c\gamma)}{(-\beta-1)\alpha^2+8I}\right]$ |
| 3 | $p$ | $\left[c+\frac{2aI-2cI}{-\alpha^2+4I}\right]$ | $\left[\frac{\left(48aI+16cI-3a\alpha^2-9c\alpha^2\right)}{4(-3\alpha^2+16I)}\right]$ | $\left[\frac{\{6I(a-c+c\gamma)\}}{(-\beta-1)\alpha^2+8I}-c(\gamma-1)\right]$ |
| 4 | $q$ | $\left[\frac{2I(a-c)}{-\alpha^2+4I}\right]$ | $\left[\frac{\left\{(-\alpha^2+16I)(a-c)\right\}}{4(-3\alpha^2+16I)}\right]$ | $\left[\frac{2I(\beta+1)(a-c+c\gamma)}{(-\beta-1)\alpha^2+8I}\right]$ |
| 5 | $\theta$ | $\left[\frac{\alpha(a-c)}{-\alpha^2+4I}\right]$ | $\left[\frac{2\alpha(a-c)}{-3\alpha^2+16I}\right]$ | $\left[\frac{\alpha(\beta+1)\left(a-c+c\gamma\right)}{(-\beta-1)\alpha^2+8I}\right]$ |
| 6 | $\psi$ | - | $\left[\frac{\alpha^2}{16I}\right]$ | - |
| 7 | $\pi^M$ | - | $\left[-\frac{\left(a-c\right)^2\left(\frac{3\alpha^4}{16}+2\alpha^2I-16I^2\right)}{(16I-3\alpha^2)^2}\right]$ | $\left[\frac{\left\{4I^2\left(a-c+c\gamma\right)^2(1+\beta)\right\}}{\left(\beta\alpha^2-8I+\alpha^2\right)^2}-v_1\right]$ |
| 8 | $\pi^R$ | - | $\left[\frac{\left(-\alpha^2+16I\right)(a-c)^2}{8(-3\alpha^2+16I)}\right]$ | $\left[\frac{\left\{I(\beta+1)\left(a-c+c\gamma\right)^2\right\}}{\left\{(-\beta-1)\alpha^2+8I\right\}}-v_2\right]$ |
| 9 | $\pi^{SC}$ | $\left[\frac{I(a-c)^2}{-\alpha^2+4I}\right]$ | $\left[\frac{\left(-\alpha^2+48I\right)(a-c)^2}{16(-3\alpha^2+16I)}\right]$ | $\left[\frac{\left\{I(\beta+1)\left(a-c+c\gamma\right)^2\left\{12I-\alpha^2(\beta+1)\right\}\right\}}{\left\{8I-\alpha^2(\beta+1)\right\}^2}-(v_1+v_2)\right]$ |

## NUMERICAL AND GRAPHICAL ANALYSIS

For the numerical simulation, we considered the following parameters: $a = 800$; $\beta = 0.33$; $\gamma = 0.25$; $c = 10$; $\bar{\pi}^{M}_{min} = 500$; $\alpha = 4$; $I = 5$; $v_1 = 200$; $v_2 = 200$. Using the numerical example, we present the effectiveness of different contracts. In this study, the parameter values of cost reduction coefficient and demand expansion coefficient are adopted from the prior study (Wang and Chan 2010). Using the model parameters adopted from the previous study (Wang and Chan 2010), quantification of decision variables and objective functions are done and presented in Table 4. Furthermore, using the joint concavity conditions, the model parameters are considered, and quantification of decision variables and objective functions are done and presented in Table 4. The conditions of joint concavity are mentioned in the appendix section. The results reveal that the VO model results in higher sustainable innovation, demand, and channel efficiency as compared to a cost-sharing contract (see Table 4).

**Table 4.** Optimal Results of Sustainable Supply Chain Coordination Model

| S. No. | Optimal Decisions | Centralized | CSC | Virtual Organization |
|---|---|---|---|---|
| 1 | *Wholesale Price of Manufacturer* | - | 405 | 430.84 |
| 2 | *Margin of Retailer* | - | 790 | 846.69 |
| 3 | *Retail Price* | 1985 | 1195 | 1277.5 |
| 4 | *Demand for Product* | 1975 | 395 | 563.04 |
| 5 | *Sustainability Level* | 790 | 197.5 | 225.22 |
| 6 | *Profit of Manufacturer* | - | 117020 | 237360 |
| 7 | *Profit of Retailer* | - | 156025 | 222110 |
| 8 | *Total Supply Chain Profit* | 780125 | 273040 | 459470 |
| 9 | *Channel Efficiency* | 1 | 0.35 | 0.59 |

Table 4 shows that the proposed virtual organization mechanism performs better than a cost-sharing contract. The level of sustainable performance in the VO model is higher than the cost-sharing contract.

### *IMPACT OF COST PARAMETER OF SUSTAINABILITY AND COST REDUCTION COEFFICIENT*

Figure 2 and Figure 3 demonstrate the impact of the cost parameter of sustainability ($I$) and cost reduction coefficient ($\gamma$) on the level of sustainability ($\theta$), total supply chain profit($\pi^{SC}$), price($p$), and demand ($q$) of product. Figure 2shows that the cost parameter of sustainability ($I$) has a decreasing impact on sustainability level($\theta$) and total supply chain profit ($\pi^{SC}$). The impact of cost reduction coefficient($\gamma$) on $\theta$ and $\pi^{SC}$ is not significant. The non-significant impact of $\gamma$ can be due to the lesser variation in the marginal cost of manufacturing or due to the impact of the higher cost of sustainable innovation,which warrants further investigations. The level of sustainability and total supply chain profit is highest in the centralized supply chain followed by a virtual organization model ($VO$), and lowest in the cost-sharing contract ($CSC$). The higher level of sustainability and total supply chain profit in the VO model with respect to the traditional cost-sharing contract may be due to the network effect of the virtual organization model.

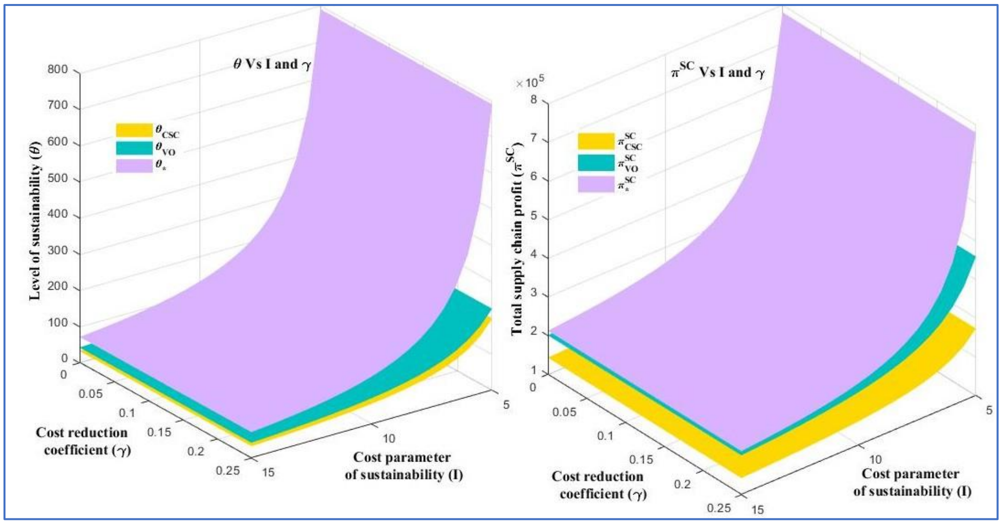


**Figure 2.** Impact of $I$ and $\gamma$ on $\theta$ and $\pi^{SC}$

The decreasing impact of $I$ on $\theta$ and $\pi^{SC}$ can be due to the higher cost of sustainable innovation. Most importantly, in the given condition, the virtual organization model always performs better than a cost-sharing contract. Figure 3 indicates the impact of $I$ and $\gamma$on the retail price ($p$) and demand ($q$) of the product. From Figure 3, it is clear that $I$ has a decreasing impact on $p$and $q$, which can be due to a lower level of sustainable innovation. The lower level of sustainability due to the higher level of $I$ leads to lower price as well as lower demand for the product (as consumers are sensitive toward sustainability). Figure 3 also reveals that the price and demand of the product are higher in the VO model as compared to the cost-sharing contract. Figure 3 shows that $\gamma$ has no significant impact on price and demand, which needs further inquiries.

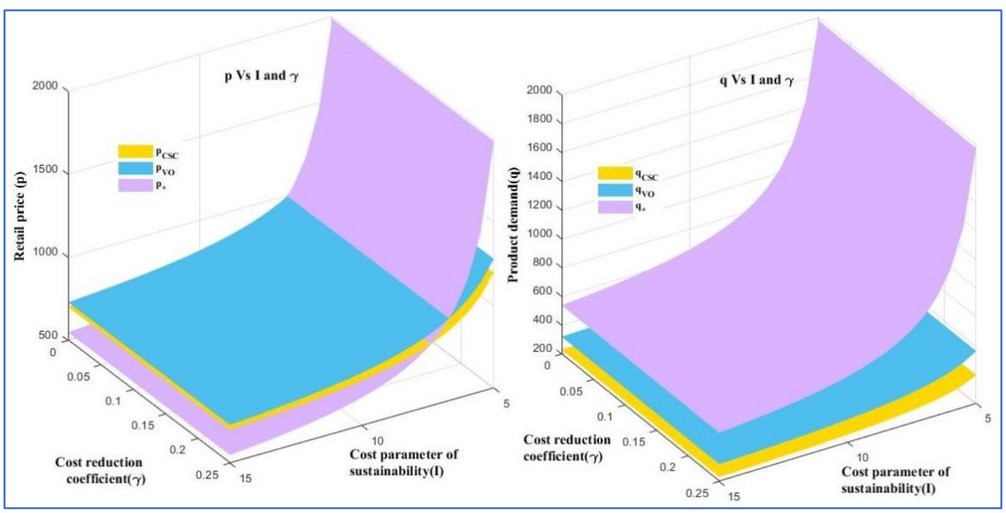


**Figure 3.** Impact of $I$ and $\gamma$ on $p$ and $q$

### *IMPACT OF SENSITIVITY TO SUSTAINABLE INNOVATION AND DEMAND EXPANSION COEFFICIENT*

Figure 4 shows the impact of consumer sensitivity to sustainable innovation $(\alpha)$ and demand expansion coefficient $(\beta)$ on the profit of manufacturer (Fig. 4(a)), the profit of retailer (Fig. 4(b)), level of sustainability (4(c)), and retail price (4(d)). These graphical analyses unravel various interesting characteristics of the proposed I4.0 based VO model. In the region 1 of Fig. 4(a), 4(b), 4(c), and 4(d), $\pi_{CSC}^{M} > \pi_{VO}^{M}$, $\pi_{CSC}^{R} > \pi_{VO}^{R}$, $\theta_{CSC} > \theta_{VO}$, and $p_{CSC} > p_{VO}$respectively. On the other hand, in the region 2 of Fig. 4(a), 4(b), 4(c), and 4(d), $\pi_{VO}^{M} > \pi_{CSC}^{M}$, $\pi_{VO}^{R} > \pi_{CSC}^{R}$, $\theta_{VO} > \theta_{CSC}$, and $p_{VO} > p_{CSC}$respectively. Therefore, for both, manufacturer and retailer, the region 2 is the favorable condition for setting their strategies to achieve the common sustainability goals of the supply chain.

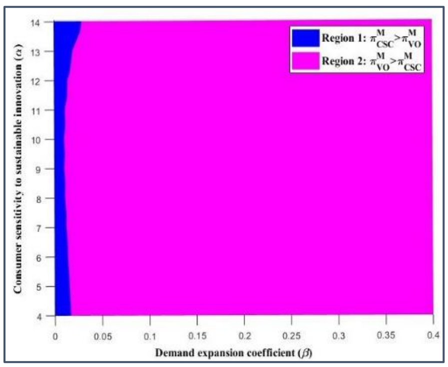


**Figure 4(a).** Impact of $\alpha$ and $\beta$ on $\pi^M$

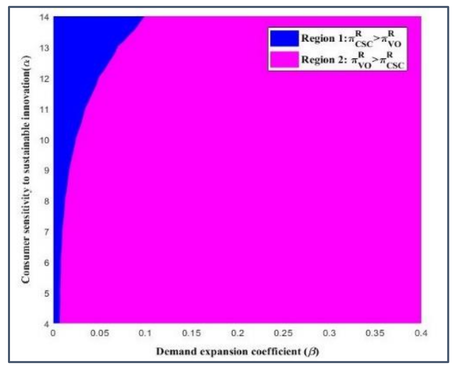


**Figure 4(b).** Impact of $\alpha$ and $\beta$ on $\pi^R$

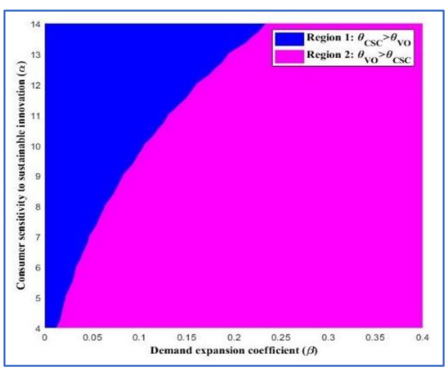


**Figure 4(c).** Impact of $\alpha$ and $\beta$ on $\theta$

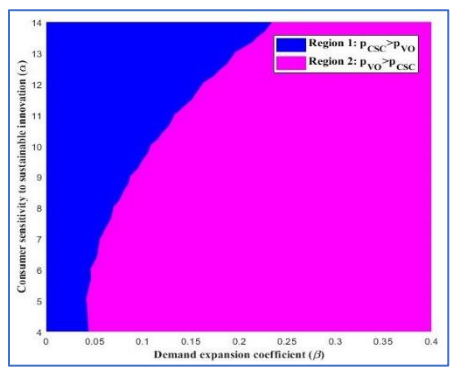


**Figure 4(d).** Impact of $\alpha$ and $\beta$ on $p$

**Figure 4.** Impact of $\alpha$ and $\beta$

Hence, in order to achieve a higher level of sustainability, as well as a higher individual profit level, both supply chain agents should invest in the virtual organization. The demand expansion coefficient $(\beta)$ factor of the virtual organization model plays a major role in achieving higher channel efficiency of the sustainable supply chain. It can be due to increased consumer participation in product development, awareness about sustainability, better demand forecasting, lead time reduction, and pin-point delivery of the product. Thus, forming I4.0 based virtual organization can be important for better coordination of sustainable supply chain as compared to traditional supply chain contracts.

## DISCUSSION

In this section, important insights from analytical results and numerical analysis are discussed. The specific focuses of the discussion section are virtual organizations in the textile industry, the effect of VO on cost and demand, and the effect of sustainable innovation on the performance of the supply chain. At the end of the discussion section, the precise guidelines for estimating the model parameters are presented.

In this study, the Industry 4.0 based VO model for the sustainable textile industry is proposed and formulated using non-cooperative game theory. The effectiveness of the proposed model is demonstrated using numerical simulations and graphical analysis. The investment in information technology is made to establish the virtual network among different channel partners such as farmers, man-made fiber production units, spinning units, weaving units, processing units, garmenting units, and so forth. The textile industry is a highly labor-intensive industry (Cai and Choi, 2020). The VO cuts front-line costs such as labor costs. Additionally, the VO supports for reducing of the inventory cost by making the balance between supply and demand and attaining the supply chain flexibility and responsiveness. Furthermore, investment in information technology to establish VO in the textile industry helps in operational cost reduction through process improvement. Additionally, this industry is struggling with the coordination and sustainability issues and primarily consists of different dominance structures. Cai and Choi (2020) also mentioned that the apparel supply chain is a long value chain with labor-intensive manufacturing and a relatively high degree of environmental pollution (Bentahar and Benzidia, 2018; Choi and Cai, 2020, Choi et al., 2018) as compared to other supply chains. The VO helps the textile supply chain to achieve coordination. Wang and Chan (2010) studied the impact of VO in the textile industry and found that VO avoids conflicts among firms and helps channel partners to share demand and order information. Furthermore, VO supports the textile firms to collect and analyze the demand information and passing the information to channel partners, which results in better visibility of market demand. The investment in information technology helps in enhancing the capability to fulfill dynamic market demand, reducing the cycle time of demand fulfillment, and developing a new market by coordination with aforementioned channel partners.

The sustainable innovation helps the supply chain to improve the net earning and growth in sales revenue (Kumar et al., 2021; Nidumolu et al., 2009; Sun et al., 2017). There exist two basic forms of sustainable innovation such as exploratory and exploitative innovation, which help in improving the environmental performance of the firms (Gibson & Birkinshaw, 2004). The exploratory component of innovation helps in developing more sustainable and new products and creating new segments in the market; on the other hand, exploitative component of sustainable innovation helps in improving existing products and technologies (Jakhar et al., 2018). Furthermore, sustainable innovation helps in the reduction in the cost due to eco-efficiency (Orsato, 2006).

In the proposed Industry 4.0 based virtual organization model, the supply chain agents form a strategic alliance using information technology. The establishment of a virtual organization needs the identification of supply chain balancing units, formation of various centers such as procurement planning center, subcontracting planning center, sales planning center, a headquarter (HQ), and integration of balancing units, cross-functional centers, and headquarter using information technology. During the establishment of VO based textile supply chain, various channel partners such as fiber supplier, ginning units, spinning units, weaving units, chemical pretreatment units, dyeing units, finishing units, and garment manufacturing units, distributors, wholesalers, and retailers are linked with centers and HQs of VO through information technology. In this way, VO improves the collection, analysis, and sharing of information regarding the specifications of market demand throughout the supply chain. Due to availability of complete information about market demand in VO

model, the cotton supplier sends the specific fiber to the spinning units. On the basis of information received from HQs of VO, and fiber received from supplier, spinning units produce exact counts of yarns, and subsequently, weaving and chemical processing and other operations are done as per the clear information received from the HQs of VO. In this way supply chain achieves flexibility in response to market demand and becomes more responsive. The proposed virtual organization model has the capabilities to resolve the problems mentioned above of forward and backward supply chain simultaneously (Wang and Chan 2010). The establishment of a virtual organization using Industry 4.0 (I4.0) is an attempt to improve the efficiency and effectiveness and overcome the complexities of the channel.

In order to quantify the effect of VO on cost and demand, the method of cost of goods sold to revenue ratio, return on investment (ROI), the percentage increase in profit, sales growth, and employee to revenue ratio can be used. Similar methods are stated in prior literature (Koh et al., 2008). These matrices will provide the measures of the impact of investment in technology (during the establishment of VO-based textile supply chain) on cost and demand. In order to quantify the effect of sustainable innovation on the performance of the supply chain, change in net earning, the percentage increase in profit, and sales growth percentage can be calculated. Similar methods are stated in prior literature (Nidumolu et al., 2009). These matrices will provide the measures of the impact of sustainable innovation on the channel performance.

## CONCLUSION

In this paper, we designed an analytical model consisting of an I4.0 based virtual organization for supply chain coordination to enhance the level of sustainability. This virtual organization-based mechanism also has the capability to improve the level of mass customization and awareness of the sustainable performance of the entire supply chain among customers through the involvement of customers in product quality decision making. In this study, we considered the retailer Stackelberg game, in which the retailer is responsible for sustainable innovation. The manufacturer and retailer are investing in information technology to form a virtual organization.

In this paper, the proposed virtual organization model is compared with a cost-sharing contract and centralized supply chain. Using numerical simulations, we demonstrated the impact of consumer sensitivity to sustainable innovation on demand, price, profits of supply chain agents, total supply chain profit, etc. We also demonstrated the impact of the cost parameter of sustainable innovation on demand, price, profits of supply chain agents, total supply chain profit, etc. In the case of the VO model, the level of sustainable innovation, order quantity, total channel profit, and supply chain efficiency is higher than the cost-sharing contract but lower than the centralized supply chain.

The results indicate that sustainable performance obtains maximum supply chain profit in a market sensitive to sustainability. However, sustainable performances require additional investment, leading to a higher price of the product. The newly designed virtual organization model may be used to reduce the total operational cost of upstream firms and to increase the market demand simultaneously. However, the formation of such the VO requires additional investment in digital technologies as well as trust and fairness among contracting supply chain agents. Therefore, the government should implement policy and promote investment in digital technologies to enhance sustainable practices.

This study has various interesting and important implications in terms of contribution to the existing literature, managerial implications, and implication for policy-makers. Table 5 presents important findings and managerial/policy implications of this study. The use of I4.0 based virtual organization in designing mechanisms for sustainable supply chain coordination is one of the most important contributions to the existing literature. This proposed mechanism can solve the problems of forward and backward supply chains simultaneously and help in achieving mass customization. The

second study provided a virtual organization model for the two-echelon sustainable supply chain and compared the virtual organization model with the existing cost-sharing contract. This study showed that the proposed virtual organization model performs better than the cost-sharing contract.

**Table 5.** Findings and Implications

| | Research Question | Findings | Managerial/Policy Implications |
|---|---|---|---|
| **(i)** | **How does the I4.0 based virtual organization model will help in achieving coordination between forward and backward supply chains?** | *We have designed and demonstrated the effectiveness of the I4.0 based VO model for supply chain coordination using non-cooperative game theory. For modelling the VO based coordination model, we incorporated two aspects of the virtual organization, first the cost reduction factor of the backward supply chain and second, the demand expansion factor of the forward supply chain.* | *Although the VO model does not lead to perfect channel coordination, it can perform better than the cost-sharing contract. Therefore, the virtualization of the supply chain can be a better strategy for improving sustainable performance.* |
| **(ii)** | **How is the Virtual organization model better than the traditional coordination mechanisms?** | *The virtual organization leads to a higher level of sustainability, demand, total supply chain profit, and channel efficiency as compared to a cost-sharing contract. Therefore, I4.0 based virtual organization model performs better than the traditional supply chain contract. The demand expansion properties of the proposed model have a major contribution to the better performance of the proposed model.* | *In the case of sustainable supply chain coordination, practitioners should adopt a virtual organization model as compared to wholesale price contract and cost-sharing contract. In the proposed model, major attention should be given to better forecasting of demand, advertisement, the involvement of customers in product quality decision making, and transparency.* |
| **(iii)** | **What will be the impact of sustainability parameters on the performance measures of the supply chain?** | *The consumer sensitivity to sustainable innovation has an increasing impact on total supply chain profit, retail price, the demand for the product, and level of sustainable innovation in retailer Stackelberg supply chain. At the lower level of consumer sensitivity to sustainable performance, virtualization of the supply chain gives better results.* | *In the market where consumers are less sensitive towards sustainable innovation, managers should focus on the formation of virtual organization to achieve better performance of the entire supply chain.* |
| **(iv)** | **How is the consumer sensitivity to sustainable performance related to the performance measures of supply chain agents?** | *The cost parameter of sustainable performance has a decreasing impact on total supply chain profit, retail price, the demand for the product, and level of sustainable innovation in retailer Stackelberg supply chain. At the higher level of cost parameter of sustainable performance, virtualization of the supply chain gives better results.* | *In the situation of higher cost parameters of sustainability, managers should focus on the formation of virtual organization to achieve better performance of the entire supply chain.* |

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## APPENDIX

### *I4.0 BASED VIRTUAL ORGANIZATION MODEL*

$$\underset{(m,\theta)}{Maximize}\{\pi^R\} = \underset{(m,\theta)}{Maximize}\{(p-w)q(1+\beta) - I\theta^2 - v_2\} \quad (1)$$

subject to,

$$w = \underset{w}{argmax}\{\pi^M\} = \underset{w}{argmax}\{\big(w - c(1-\gamma)\big)q - v_1\} \quad (2)$$

We follow the backward induction method to calculate the optimal value of decision variables. Differentiating $\pi^M$w.r.t. , we get, $\frac{d\pi^M}{dw} = (\beta+1)(a-m-w+\alpha\theta) - (w + c(\gamma-1))(\beta+1)$. Taking second order derivative of eq(13), gives $\frac{d^2\pi^M}{dw^2} = -2\beta - 2 < 0$. Therefore, $\pi^M$ will be concave in $w$. Thus, the first-order condition of $\frac{d\pi^M}{dw}$gives $w^* = \frac{(\beta+1)(a-m+\alpha\theta) - c(\beta+1)(\gamma-1)}{2\beta+2}$. Putting the value of $w^*$in $\pi^R = \{(p-w)q(1+\beta) - I\theta^2 - v_2\}$, and after rearrangement, we get, $\pi^R = m(\beta+1)\Big(a - m + \alpha\theta - \frac{(\beta+1)*(a-m+\alpha\theta) - c(\beta+1)(\gamma-1)}{2\beta+2}\Big) - \theta^2 I - v_2$. Now, after calculating first order and second-order partial derivative of $\pi^R$ w.r.t. $m$ and $\theta$, we get following, $\frac{\partial\pi^R}{\partial m} = (\beta+1)\Big(a - m + \alpha\theta - \frac{(\beta+1)(a-m+\alpha\theta) - c(\beta+1)(\gamma-1)}{2\beta+2}\Big) + m\Big(\frac{\beta+1}{2\beta+2} - 1\Big)(\beta+1)$, $\frac{\partial\pi^R}{\partial\theta} = m(\beta+1)\Big(\alpha - \frac{\alpha(\beta+1)}{2\beta+2}\Big) - 2I\theta$, $\frac{\partial^2\pi^R}{\partial m^2} = H_{1\times1} = -(\beta+1) < 0$, $\frac{\partial^2\pi^R}{\partial\theta^2} = H_{1\times1} = -2I < 0$. The Hessian matrix of $\pi^R$w.r.t. to $m$ and $\theta$ is defined as, $H_{2\times2} = \Big(2I + 2\beta I - \frac{\beta\alpha^2}{2} - \frac{\alpha^2}{4} - \frac{\beta^2\alpha^2}{4}\Big)$. Therefore, if $\Big(2I + 2\beta I - \frac{\beta\alpha^2}{2} - \frac{\alpha^2}{4} - \frac{\beta^2\alpha^2}{4}\Big) > 0$, then $\pi^R$will be jointly concave in $m$ and $\theta$, and simultaneous solution of $\frac{\partial\pi^R}{\partial m} = 0$ and $\frac{\partial\pi^R}{\partial\theta} = 0$, will give equilibrium results. This completes the proof of equilibrium results of I4.0 based virtual organization model.

### *CENTRALIZED SUPPLY CHAIN*

$$\underset{(p,\theta)}{\text{Maximize}}\pi^{CENT} = \underset{(p,\theta)}{\text{Maximize}}\{(p-c)q - I\theta^2\} \quad (3)$$

Where $q = (a - p + \alpha\theta)$. After taking, first order and second order partial differentiation of $\pi^{CENT} = \{(p-c)q - I\theta^2\}$,with respect to $p$ and $\theta$ , we get, $\frac{\partial\pi^{CENT}}{\partial p} = a + c - 2p + \alpha\theta$, $\frac{\partial\pi^{CENT}}{\partial\theta} = -2\theta I - \alpha(c-p)$, $\frac{\partial^2\pi^{CENT}}{\partial p^2} = -2 < 0$, and $\frac{\partial^2\pi^{CENT}}{\partial\theta^2} = -2I < 0$. The Hessian matrix of $\pi^{CENT}$ with respect to $p$ and $\theta$ is defined as follow: $H_{2\times2} = -\alpha^2 + 4I$. If $(-\alpha^2 + 4I) > 0$, then $\pi^{CENT}$ will be jointly concave in $p$ and $\theta$, and simultaneous solution of $\frac{\partial\pi^{CENT}}{\partial p} = a + c - 2p + \alpha\theta = 0$, and $\frac{\partial\pi^{CENT}}{\partial\theta} = -2\theta I - \alpha(c-p) = 0$, give $p^{CENT} = c + \frac{2aI - 2cI}{-\alpha^2 + 4I}$, and $\theta^{CENT} = \frac{\alpha(a-c)}{-\alpha^2 + 4I}$. Putting value of $p^{CENT}$, and $\theta^{CENT}$ in $q = (a - p + \alpha\theta)$, and we get $q^{CENT} = \frac{2I(a-c)}{-\alpha^2 + 4I}$. Finally, Putting the value of $p^{CENT}$, $q^{CENT}$, and $\theta^{CENT}$ in $\pi^{CENT} = \{(p-c)q - I\theta^2\}$, we get $\pi^{CENT} = \frac{I(a-c)^2}{-\alpha^2 + 4I}$. This completes the proof of equilibrium results of a centralized supply chain.

***COST SHARING CONTRACT***

$$\underset{\psi}{\text{Maximize}}\{\pi^M\} = \underset{\psi}{\text{Maximize}}\{(w-c)q - \psi I\theta^2\} \tag{4}$$

subject to

$$\underset{(m,\theta)}{\text{Maximize}}\{\pi^R\} = \underset{(m,\theta)}{\text{Maximize}}\{(p-w)q - (1-\psi)I\theta^2\} \tag{5}$$

subject to

$$w = \underset{w}{argmax}\{\pi^M\} = \underset{w}{argmax}\{(w-c)q - \psi I\theta^2\} \tag{6}$$

We follow the backward induction method to calculate the optimal value of decision variables. Differentiating $\pi^M = \{(w-c)q - \psi I\theta^2\}$ w.r.t.$w$, we get, $\frac{d\pi^M}{dw} = (a + c - m - 2w + \alpha\theta)$. Taking second-order derivative of $\pi^M$ w.r.t. $w$, gives $\frac{d^2\pi^M}{dw^2} = -2 < 0$. Therefore, $\pi^M$ will be concave in $w$. Thus, the first-order condition of $\frac{d\pi^M}{dw}$gives $w = \left(\frac{a}{2} + \frac{c}{2} - \frac{m}{2} + \frac{\alpha\theta}{2}\right)$. Therefore, $p = (w+m) = \left(\frac{a}{2} + \frac{c}{2} + \frac{m}{2} + \frac{\alpha\theta}{2}\right)$. Similarly, $q = (a - p + \alpha\theta) = \left(\frac{a}{2} - \frac{c}{2} - \frac{m}{2} + \frac{\alpha\theta}{2}\right)$. Putting value of $w^*$, $p$, and $q$ in $\pi^R = \{(p-w)q - (1-\psi)I\theta^2\}$, we get, $\pi^R = m\left(\frac{a}{2} - \frac{c}{2} - \frac{m}{2} + \frac{\alpha\theta}{2}\right) - \theta^2 I(1-\psi)$. Taking first order and second-order partial derivatives of $\pi^R$w.r.t. m and $\theta$, we get, $\frac{\partial\pi^R}{\partial m} = \left(\frac{a}{2} - \frac{c}{2} - m + \frac{\alpha\theta}{2}\right)$, $\frac{\partial\pi^R}{\partial\theta} = \left\{\frac{\alpha m}{2} - 2\theta I(1-\psi)\right\}$, $\frac{\partial^2\pi^R}{\partial m^2} = H_{1\times1} = -1 < 0$, $\frac{\partial^2\pi^R}{\partial\theta^2} = H_{1\times1} = -2I(1-\psi) < 0$. The Hessian matrix of $\pi^R$w.r.t. to $m$ and $\theta$ is defined as, $H_{2\times2} = \left(-\frac{\alpha^2}{4} + 2I - 2\psi I\right)$. Therefore, if $\left(-\frac{\alpha^2}{4} + 2I - 2\psi I\right) > 0$, then $\pi^R$will be jointly concave in $m$ and $\theta$, and simultaneous solution of $\frac{\partial\pi^R}{\partial m} = 0$ and $\frac{\partial\pi^R}{\partial\theta} = 0$, will give, $m = -\frac{4(aI - cI - a\psi I + c\psi I)}{\alpha^2 - 8I + 8\psi I}$, and $\theta = -\frac{\alpha(a-c)}{\alpha^2 - 8I + 8\psi I}$. Putting the value of $m$ and $\theta$ in $w, p, q$, and $\pi^M$, we get, $w = \left[\frac{a}{2} + \frac{c}{2} + \frac{2(aI - cI - a\psi I + c\psi I)}{\alpha^2 - 8I + 8\psi I} - \frac{\alpha^2(a-c)}{2(\alpha^2 - 8I + 8\psi I)}\right]$, $p = \left[\frac{a}{2} + \frac{c}{2} - \frac{2(aI - cI - a\psi I + c\psi I)}{\alpha^2 - 8I + 8\psi I} - \frac{\alpha^2(a-c)}{2(\alpha^2 - 8I + 8\psi I)}\right]$, $q = \left[\frac{a}{2} - \frac{c}{2} + \frac{2(aI - cI - a\psi I + c\psi I)}{\alpha^2 - 8I + 8\psi I} - \frac{\alpha^2(a-c)}{2(\alpha^2 - 8I + 8\psi I)}\right]$, and $\pi^M = \frac{I(a-c)^2(-\alpha^2\psi + 4I\psi^2 - 8I\psi + 4I)}{(\alpha^2 - 8I + 8\psi I)^2}$. Now, first order and second-order differentiation of $\pi^M$ with respect to $\psi$ gives, $\frac{d\pi^M}{d\psi} = \frac{\alpha^2 I(a-c)^2(-\alpha^2 + 16\psi I)}{(\alpha^2 - 8I + 8\psi I)^3}$, and $\frac{d^2\pi^M}{d\psi^2} = -\frac{8\alpha^2 I^2(a-c)^2(-5\alpha^2 + 16I + 32\psi I)}{(\alpha^2 - 8I + 8\psi I)^4} < 0$, therefore, $\pi^M$ is concave in $\psi$. Thus, $\frac{d\pi^M}{d\psi} = 0$, gives $\psi = \frac{\alpha^2}{16I}$, which maximize $\pi^M$. Putting $\psi = \frac{\alpha^2}{16I}$ in w, m, p, q, $\theta$, $\pi^M$and $\pi^R$, we get equilibrium results. This completes the proof of equilibrium results of the cost-sharing contract.